Double species condensate with tunable interspecies interactions

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We produce Bose-Einstein condensates of two different species, ^{87}Rb and ^{41}K, in an optical dipole trap in proximity of interspecies Feshbach resonances. We discover and characterize two Feshbach resonances, located around 35 and 79 G, by observing the three-body losses and the elastic cross-section. The narrower resonance is exploited to create a double species condensate with tunable interactions. Our system opens the way to the exploration of double species Mott insulators and, more in general, of the quantum phase diagram of the two species Bose-Hubbard model.

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Ultracold atomic gases seem uniquely suited to experimentally realize and investigate physics long studied in the domain of condensed matter and solid state physics, with the distinct advantage that specific effects are better isolated from unnecessary complications often present in condensed samples. The paradigmatic superfluid to Mott insulator transition of a condensate in an optical lattice [1] confirmed the predictions of the Bose-Hubbard model [2, 3], originally introduced to describe superfluid Helium. With two species, the zero-temperature diagram of quantum phases is much richer than the simple duplication of the single species' [4]. Indeed it has been proposed that two species obeying an extended Bose-Hubbard model can mimick the physics of lattice spins described by the Heinsenberg model [5, 6] and give rise to yet unobserved quantum phases, like the double Mott insulator and the supercounterflow regime [7], with peculiar transport properties. Therefore, a double species condensate in an optical lattice stands as a promising candidate system for quantum simulations. Recently, the investigation of the two-species BH was started from the regime where one species exhibits the loss of phase coherence usually associated with the Mott insulator transition, while the other is completely delocalized [8]. Already at this stage, the presence of two species leads to a surprising shift of the critical point, which is now object of intense theoretical work [9].

In addition, a double Mott insulator is expectedly extremely useful to produce heteronuclear polar molecules [10], since the association efficiency strongly depends on the phase space overlap of the two species [11]. The rapid losses of associated molecules observed for bosonic systems could be largely suppressed by the presence of the three-dimensional optical lattice [12], if most of the sites are occupied with only one atom per species. Both these research avenues require the dynamic control of *interspecies* interactions, along with a well established collisional model.

In this Letter, we report the production of the first double species condensate with tunable interspecies interactions. A mixture of two condensates in different internal states of the same isotope was realized long ago [13] and more recently Bose-Einstein condensation (BEC) of two different atomic species has been demonstrated in a harmonic potential [14, 15] and in a three-dimensional optical lattice [8]. Providing Bose-Bose mixtures with the additional tool of tunable interspecies interactions available, this work meets a long sought goal.

To control the interactions, we investigate two heteronuclear Feshbach resonances predicted [16, 17], but yet unobserved, for both ^{87}Rb and ^{41}K in the $|F=1, m_f=1\rangle$ state below 100 G. These Feshbach resonances are interesting in themselves, since the accurate determination of the K-Rb potential curves for the singlet $X^1\Sigma^+$ and triplet $a^3\Sigma^+$ states has been recently debated [16, 17]. Indeed, extensive Feshbach spectroscopy on the mixture ^{87}Rb-^{40}K was performed by two different groups [18, 19]. Until recently, however, data on other isotopomers, crucial to pinpoint the controversial number of bound states of the singlet potential, were not available. Together with the observation of several Feshbach resonances for the ^{87}Rb-^{39}K mixture [17], our measurements are important to settle the question of the number of singlet bound states and to assess the validity of the mass scaling techniques, based on the Born-Oppenheimer approximation.

Since our setup has been described earlier [20, 21], here we briefly illustrate the experimental procedure. In separate vacuum chambers, each atomic species, ^{87}Rb and ^{41}K, is coaxed into a cold atomic beam by means of two-dimensional magneto-optical traps (2D-MOT's). The two atomic beams merge with an angle of 160° at the center of a third vacuum chamber and load a double species 3D-MOT. After 50 ms of compressed MOT and 5 ms of optical molasses, both species are optically pumped to the $|F=2, m_F=2\rangle$ state and loaded into a quadrupole trap with axial gradient equal to 260 G/cm. A motorized translation stage moves the quadrupole coils

by 26 mm and atoms are transferred to our Ioffe millimetric trap [22]. For 15.5 s, a microwave field evaporates only ^{87}Rb, while thermal equilibrium with ^{41}K is enforced by efficient interspecies collisions.

To access Feshbach resonances we transfer the atoms in a crossed dipole trap. At the end of microwave evaporation, we ramp up two horizontal orthogonal beams of waists $\sim 100\,\mu$m, delivered by a single-frequency laser at 1064 nm, in 250 ms, and then slowly estinguish the magnetic trap current. At this stage we have $3 \cdot 10^5$ atoms of ^{87}Rb and $2 \cdot 10^4$ atoms of ^{41}K. For ^{87}Rb atoms, the optical trap has a depth of $7\,\mu$K and harmonic frequencies equal to $\vec{\omega} \simeq 2\pi \times (100, 140, 100)$ Hz. Starting from a thermal single-species ^{87}Rb sample at 350 nK, we measured the lifetime and the heating rate of our crossed dipole trap to be 20 s and 20 nK/s.

In order to transfer the atoms to $|1,1\rangle$ state, we apply a 6.8 GHz microwave and a 269 MHz radiofrequency sweep (adiabatic passage), in presence of a polarizing magnetic field of 7 G: the transfer efficiency is 90(80)% for ^{87}Rb (^{41}K). In the $|1,1\rangle + |1,1\rangle$ lowest Zeeman state the mixture is stable against two-body collisions. Once completed the hyperfine transfer, ^{87}Rb atoms remaining in $|2,2\rangle$ are expelled from the optical trap by pulsing a beam resonant with the closed $|2,2\rangle \to |3,3\rangle$ transition: their presence would lead to spin changing collisions with ^{41}K releasing the ^{87}Rb hyperfine energy (0.33 K). For ^{41}K, instead, we omit to expel the remaining $|2,2\rangle$ atoms, because their absolute number is low and they are immune from spin changing collisions with ^{87}Rb due to energy conservation.

At this stage, to observe the interspecies Feshbach resonances, we ramp up the applied magnetic field in 10 ms, hold the atoms for 500 ms, abruptly switch off the optical dipole trap, and image separately the clouds after expansion times of 5 to 10 ms. We observe the enhanced three-body losses associated with the Feshbach resonances, which are best detected as a drop of the number of the minority fraction, i.e. ^{41}K. To avoid the complications arising from the dynamics driven by mean-field interactions coupled to the differential sag between the two species, we detect the losses with thermal clouds at $\sim 1\,\mu$K.

We scan the magnetic field in the range 0-90 G and we detect two Feshbach resonances, around 35 and 79 G, see Fig. 1. We fit the loss features with Gaussian functions of the magnetic field. For the broader feature around 35 G, we add a linear pedestal, that takes into account the depolarization of the ^{41}K sample, caused by incomplete suppression of laser light resonant at zero magnetic field. The loss peaks occur at (35.2 ± 1.6) and (78.61 ± 0.12) G [23] and the widths are (5.1 ± 1.8) and (0.35 ± 0.14) G, respectively. We calibrate the magnetic field by measuring the frequency of ^{87}Rb hyperfine transitions; the associated systematic uncertainty is 0.4 G.

We compare the observed Feshbach resonances positions with the theoretical predictions, shown in Fig. 2, of the collisional model of Ref. [17], yielding resonance positions equal to (39.4 ± 0.2) and (78.92 ± 0.09) G. In particular, the position of the narrower loss feature around 79 G agrees very well with the theoretical value of the Feshbach resonance. For the broader feature, the measured three-body losses are maximum at a field slightly below the theoretical prediction. We lack a conclusive explanation for this difference, we merely remark that the modeling of the three-body losses is complicated and, as a general rule, for broad resonances the loss peak can be offset from the resonance position.

In view of the application of these Feshbach resonances to tune the mixture around the non-interacting regime,

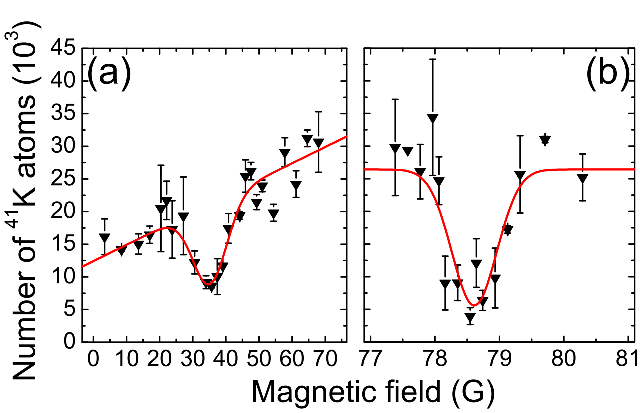

FIG. 1: (Color online): Losses of ^{41}K atoms associated with interspecies ^{87}Rb-^{41}K Feshbach resonances. The solid (red) line shows the results of Gaussian fits, yielding the peak values: (a) $B_0 = (35.2 \pm 1.6)$ G, (b) $B_0 = (78.61 \pm 0.12)$ G.

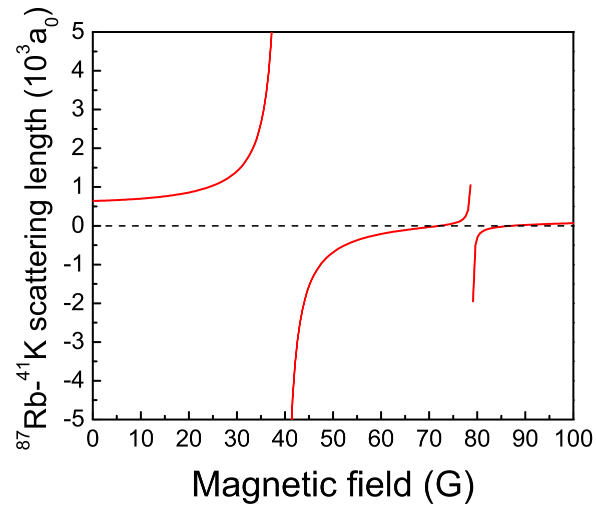

FIG. 2: (Color online): Theoretical predictions of the ^{87}Rb-^{41}K interspecies scattering length a_{12} [17], with both species in the $|1,1\rangle$ lowest Zeeman state.

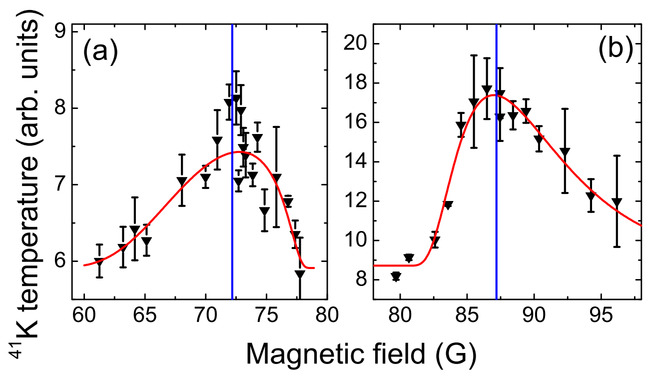

FIG. 3: (Color online): Measurement of the magnetic field of vanishing a_{12} (zero-crossing). The ^{41}K temperature after sympathetic cooling with ^{87}Rb is fit (red line) with the function $T_{\rm eq} + \Delta T \exp(-\eta(a_{12}(B-\delta B))^2)$. a_{12} as a function of B is derived by the theory, $T_{\rm eq}, \Delta T, \eta, \delta B$ are fitting parameters. The vertical (blue) lines indicate the zero-crossing theoretical predictions: 72.18 G (a) and 87.19 G (b).

e.g. for producing a double species Mott insulator phase, it is of special interest to locate the *zero-crossings* of the interspecies scattering length a_{12}, i.e. the magnetic field values where a_{12} vanishes. To this end, we studied the efficiency of sympathetic cooling of ^{41}K by ^{87}Rb [24]. For this, we applied an additional evaporation stage by lowering the optical trap power to 50% in 1.5 s. Even though the optical potential is 10% larger for ^{87}Rb, the combined optical and gravitational potential makes the optical trap deeper for ^{41}K. Therefore by lowering the trap depth, we evaporate mostly ^{87}Rb and rely on sympathetic cooling for ^{41}K.

During the thermalization the temperature of ^{41}K decreases exponentially with a rate proportional to the interspecies elastic cross section [25], proportional to a_{12}^2, hence the final temperature of the ^{41}K cloud $T_{41}^{\rm fin}$ is a decreasing function of a_{12}^2: $T_{41}^{\rm fin} = T_{\rm eq} + \Delta T \exp(-\eta a_{12}^2)$, where η is a parameter depending on the overlap density and the thermalization time. We fit our data with the above simple model where the dependence of a_{12} on the magnetic field is taken from the theory. In addition to $T_{\rm eq}, \Delta T$ and η, we introduce another fit parameter δB allowing for a global offset of the magnetic field values, to quantitatively verify the agreement of our data with the theoretical predictions. In Fig. 3, we show the data plot along with the fit. Since the δB fit values equal (0.59 ± 0.64) for Fig. 3(a) and (-0.21 ± 0.32) G for Fig. 3(b), we conclude that the zero-crossing measurements are in good agreement with the theoretical predictions.

With the benefit of the controlled interspecies interactions arising from such favorable Feshbach resonances below 100 G, we have been able to produce the double species condensate on both sides of the narrow Feshbach resonance. For this, we slightly modify the final stages of evaporation and sympathetic cooling, that must be adjusted for the targeted value of interspecies scattering length. For example, to achieve BEC on the repulsive side, we first ramp the magnetic field to 77.7 G in 40 ms, where expectedly $a_{12} \simeq 250 a_0$. We then evaporate the mixture by lowering the optical trap power in 3 s. During the last 500 ms of evaporation, the magnetic field is brought to 76.8 G ($a_{12} \simeq 150 a_0$), to reduce the rate of three-body losses. With this scheme, we produced pure double species condensates with typically $9(5) \cdot 10^3$ ^{87}Rb (^{41}K) atoms. In alternative, we achieve a double condensate, with the same typical number of atoms, by performing the optical evaporation at 80.7 G, where $a_{12} \simeq -185 a_0$.

This fact highlights an important feature of our setup. At the end of evaporation, the measured harmonic frequency of the dipole trap along the vertical direction equals 84 Hz (for ^{87}Rb) and the trap centers for the two clouds are 13 μm apart, due to the differential gravity sag. By suitably balancing the number of atoms, we arrange BEC to occur first for ^{41}K. Shortly afterwards, the two clouds separate and ^{87}Rb reaches BEC. This separation, that can be reversed by recompressing the trap at the end of the evaporation, allows us to avoid all mean-field dynamics induced by interactions between the two species, like the phase separation(collapse) expected for large positive(negative) a_{12} [26]. At variance, striking manifestations of mean-field effects were observed in a recent experiment: in a ^{87}Rb-^{85}Rb double condensate, tuning the ^{85}Rb scattering length leads to phase-separation and formation of long-lived droplets [27]. Indeed, the solution of coupled Gross-Pitaevskii equations shows that the mean-field interactions dictate the equilibrium configuration through the parameter $\Delta = (a_1 a_2 / a_{12}^2) - 1$. This parameter can be tuned by varying either a_1 or a_{12}. However, for the purpose of exploration of the phase diagram and molecular association, tuning the single-species scattering length is not sufficient and the ability of varying a_{12} is required.

For this goal our ^{87}Rb-^{41}K mixture is especially valuable, because to date it represents the only heteronuclear Bose-Bose mixture where an interspecies Feshbach

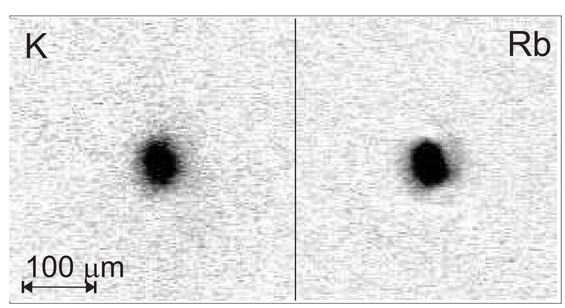

FIG. 4: Double species condensate: both species are in the $|1,1\rangle$ state. The image is taken after 9 ms of expansion.

resonance is accessible with stable condensates of both species. Particularly important is the possibility, here demonstrated, to precisely control a_{12} around zero. The observed zero-crossings appear relatively comfortable, as the slope is respectively of 16.8 and 8.9 a_0/G, and we foresee a control on a_{12} within a precision better than $1a_0$.

In conclusion, we have experimentally observed two Feshbach resonances at low (<100 G) magnetic fields, for the mixture ^{87}Rb-^{41}K in the lowest Zeeman state. These Feshbach resonances allowed us to create the first double species Bose condensate with tunable interspecies interactions. Combined with a three-dimensional optical lattice, which we have already implemented and used [8], this tool will enable the exploration of the two-species BH phase diagram. For this purpose, we measured the position of two zero-crossings of the interspecies scattering length.

The Feshbach resonance around 79 G appears well suited to create molecules by sweeping the magnetic field, due to its narrow width of 1.2 G. On the other hand, the broad resonance at lower magnetic field might be more favorable for radiofrequency molecular association, since the energy separation ΔE of the bound state from the free atoms threshold increases very slowly with the magnetic field detuning from resonance $B - B_o$, i.e. $\Delta E \simeq -0.005\mu_B(B - B_0)$.

Finally, our heteronuclear mixture with tunable interactions will allow the investigation of the intriguing physics of a superfluid interacting in a controlled way with a material grating, constituted by localized bosonic atoms in a deep periodic optical potential. For such systems, polarons growth and dynamics are currently under theoretical analysis [28].

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[1] M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature **415**, 39 (2002).
[2] M. P. A. Fisher, P. B. Weichman, G. Grinstein, and D. S. Fisher, Phys. Rev. B **40**, 546 (1989).
[3] D. Jaksch, C. Bruder, J.I. Cirac, C.W. Gardiner, and P. Zoller, Phys. Rev. Lett. **81**, 3108 (1998).
[4] O. E. Alon, A. I. Streltsov, and L. S. Cederbaum Phys. Rev. Lett. **95**, 030405 (2005).
[5] E. Altman, W. Hofstetter, E. Demler and M. D. Lukin, New J. Phys. **5**, 113 (2003).
[6] A. Isacsson, Min-Chul Cha, K. Sengupta, and S. M. Girvin, Phys. Rev. B **72**, 184507 (2005).
[7] A. Kuklov, N. Prokoféev, and B. Svistunov, Phys. Rev. Lett. **92**, 050402 (2004);
[8] J. Catani, L. De Sarlo, G. Barontini, F. Minardi, M. Inguscio, Phys. Rev. A **77**, 011603(R) (2008).
[9] P. Buonsante, S.M. Giampaolo, F. Illuminati, V. Penna, and A. Vezzani, e-print arXiv:cond-mat/0801.3465v3.
[10] B. Damski, L. Santos, E. Tiemann, M. Lewenstein, S. Kotochigova, P. Julienne, and P. Zoller, Phys. Rev. Lett. **90**, 110401 (2003).
[11] E. Hodby, S. T. Thompson, C. A. Regal, M. Greiner, A. C.Wilson, D. S. Jin, E. A. Cornell, and C. E.Wieman, Phys. Rev. Lett. **94**, 120402 (2005).
[12] G. Thalhammer, K. Winkler, F. Lang, S. Schmid, R. Grimm, and J. H. Denschlag, Phys. Rev. Lett. **96**, 050402 (2006);
[13] C. J. Myatt, E. A. Burt, R. W. Ghrist, E. A. Cornell, and C. E. Wieman, Phys. Rev. Lett. **78**, 586 (1997).
[14] G. Modugno, M. Modugno, F. Riboli, G. Roati, and M. Inguscio, Phys. Rev. Lett. **89**, 190404 (2002).
[15] S. B. Papp and C. E. Wieman, Phys. Rev. Lett. **97**, 180404 (2006).
[16] A. Pashov, O. Docenko, M. Tamanis, R. Ferber, H. Knockel, and E. Tiemann, Phys. Rev. A **76**, 022511 (2007).
[17] A. Simoni, M. Zaccanti, C. D'Errico, M. Fattori, G. Roati, M. Inguscio, and G. Modugno, e-print arXiv:cond-mat/0803.0651v1.
[18] F. Ferlaino, C. D'Errico, G. Roati, M. Zaccanti, M. Inguscio, G.Modugno, and A. Simoni, Phys. Rev. A **73**, 040702(R) (2006); **74**, 039903(E) (2006).
[19] C. Klempt, T. Henninger, O. Topic, J. Will, W. Ertmer, E. Tiemann, and J. Arlt, Phys. Rev. A **76**, 020701(R) (2007).
[20] J. Catani, P. Maioli, L. De Sarlo, F. Minardi, M. Inguscio Phys. Rev. A **73**, 033415 (2006).
[21] L. De Sarlo, P. Maioli, G. Barontini, J. Catani, F. Minardi, and M. Inguscio, Phys. Rev. A **75**, 022715 (2007).
[22] R. Wang, M. Liu, F. Minardi, and M. Kasevich, Phys. Rev. A **75**, 013610 (2007).
[23] All statistical fit uncertainities in this manuscript correspond to a 95% confidence interval, i.e. 3 standard deviations.
[24] M. Zaccanti, C. D'Errico, F. Ferlaino, G. Roati, M. Inguscio, and G. Modugno, Phys. Rev. A **74**, 041605(R) (2006).
[25] M. Mudrich, S. Kraft, K. Singer, R. Grimm, A. Mosk, and M. Weidemüller, Phys. Rev. Lett. **88**, 253001 (2002); M. Anderlini and D. Guéry-Odelin, Phys. Rev. A **73**, 032706 (2006).
[26] F. Riboli and M. Modugno, Phys. Rev. A **65**, 063614 (2002).
[27] S. B. Papp, J. M. Pino, and C. E. Wieman, e-print arXiv:cond-mat/0802.2591v1.
[28] M. Bruderer, A. Klein, S. R. Clark, and D. Jaksch, Phys. Rev. A**76**, 011605(R) (2007).